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A Strength and Deformation Model for Timber Loaded in Compression Perpendicular to Grain

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Abstract: In design of timber structures the compressive strength and deformation perpendicular to the grain, especially at bearings, is a common design feature. Accurate strength and stiffness models are lacking in all present design codes. This study presents a physical strength and deformation model based on spreading of the bearing stresses which, in a unique way, is able to cover most practical load cases and is also simple in application and sufficiently accurate for practice. Deformation models are scarce and are not reliable enough to be accepted by the leading structural timber design codes in the world. Evaluating the models using an extensive data base of test results comprising test pieces of Spruce and five hardwood wood species, it is concluded that the proposed models show the best performance in strength and deformation prediction. The background is given how these models fit into the proposed design regulations of the new generation Eurocode5.

1. Introduction

In building practice with timber, perpendicular to grain load (CPG) load situations occur in many places. They can be found where timber beams (joists) find support, or where studs in timber frames load the bottom and top rail perpendicular to grain. In pre-stressed timber bridge decks, a relatively high pre-stress in CPG causes friction that keeps the individual bridge desk laminations together. Currently, structural timber designers are looking for ways to design higher timber frame houses and even multi-storey mid high-rise buildings, where knowledge about strength and deformation of bearing supports becomes increasingly important.

In modern structural design codes, a distinction is made between Ultimate and Serviceability Limit States. Ultimate Limit States (ULS) correspond to failure of the whole structure, or part of it, and is therefore a safety issue. SLS correspond to unacceptable deformation behaviour at normal use. An example of exceeding SLS is deflections that are visually or functionally unacceptable. There are quite precise requirements regarding ULS. For SLS, on the contrary, there are no precise requirements, as these are not safety related. It is to a large extent left to the designer, in consultation with the client, to decide on the limits. It is a matter of tra-
dition and taste whether a certain deformation is acceptable or not. Although not leading to direct structural failure, CPG deformations can create substantial damage to neighbouring building components that do not follow the bearing deformation. Knowledge about shrinkage, the elastic and creep deformation, including mechanic-sorption, are key ingredients for a successful estimation of the total bearing deformation during the life-time of a structure. The load cases evaluated in this study are given in Figure 1 where load case A represents the standardized test piece for the determination of the CPG strength and stiffness.

Figure 1: Load cases evaluated.

2. Definition of CPG strength and stiffness

An important task for CEN (European Standardization Committee), in the field of timber structures (TC124), has been to draft standards for the determination of the basic material properties such as tensile and compressive strength and stiffness parallel to grain and shear strength. A point of discussion regarding CPG properties has been whether the standards should aim at either getting well-defined basic material properties or reflect typical uses. Europe has opted for the former (the scientific) approach, assuming that it would then be possible to calculate the behaviour in practical use situations, whilst US/Canada and Australia/New Zealand have chosen the latter (the technological). This is shown by test standard CEN EN408:2010 [1] as it prescribes for CPG a method where a block of timber is loaded in uniform compression over the full surface Fig. 2(left), whereas the American (ASTM) test standard D143 method [2], Fig. 2 (right) dates from 1926 and is based on a pragmatic, technological approach in which the test piece is a timber block of 51x51x152mm (2”x2”x6”) and the load is applied in the middle through a steel plate of 51x51mm. This test is primarily intended to simulate the behaviour of a wood joist resting on a wall or foundation, Bodig & Jayne [3], and does not intend to determine a physically correct perpendicular to grain strength. When FEM calculations require input of the CPG strength it is therefore wrong to choose values derived with the ASTM D143 method.
Figure 2: CEN EN408 block test (left) ASTM D143 rail test (right).

In the absence of any model to modify the ASTM D143 [2] strength results to account for situations deviating from the test set up, empirical modification factors were established and reported for example by Kunesh [4]. Madsen et al. [5], also took an interest in the relation between deformation and compressive strength and recognised shortcomings of the ASTM method. The differences in test specimen dimension and loading configuration between the CEN EN 408 [1] and ASTM D143 [2] standards, cause major variants. In a comparative study by Pousse et al. [6], using the same wood species, a mean standard CPG strength of 2.8 MPa for the uniform compression test according to CEN EN 408 [1] was found, compared to 7.0 MPa according to ASTM D143[2].

Having established the standard compressive strength and stiffness these values form important input parameters for the design models. In Leijten and Jorissen [7], it is shown that the prescribed test specimens, in the tests standards of North America and Australia/New Zealand, are unsuitable for the determination of a correct physical stiffness for this purpose. For this reason, the strength and stiffness results obtained with CEN EN408:2010 [1] are taken as the starting point for the evaluation of the models presented in this study. Some notes about the test procedure. During the test, the total deformation together with the applied load results in a load-deformation curve, Figure 3, left.

Figure 3: Load deformation plot according to EN408:2010[1], load case A (left) and a test results for load case B (right).
The compressive force $F_{c,90}$, from which the CPG strength $f_{c,90}$ is derived, is defined by the intersection of a line parallel to the linear elastic part of the load-deformation curve, off-set by 1% of the specimen depth, $h$. This straight line is used to calculate the modulus of elasticity of the standard test specimen, $E_{90}$. If the value of $E_{90}$ is used to determine the deformation at the defined $F_{c,90}$, then this value has to be reduced which leads to the introduction of an apparent modulus of elasticity, $kE_{90}$ with $k < 1$.

A typical experimentally determined load-deformation curve for load case B is given in Figure 3, right. The determination of the CPG strength follows the same procedure as for the standard test piece, but now the off-set line is 1% of the full beam depth for load case B. The deformation associated with this CPG strength is $\delta$, as is given in the figure, which does not include any delayed load uptake at the beginning of the load application. This deformation is recorded and is later compared with the model predictions.

In this respect, it is time to address a shortcoming of the standard test procedure of EN408:2010 [1] that affects the determination of the modulus of elasticity perpendicular to grain. It might seem logical to take as deformation the total deformation (over the full depth) of the standard test piece and similarly measure the total deformation of any other test piece. The gauge length to record the deformation currently prescribed by EN408:2010, however, is set to 60% of the specimen depth. Bodig and Jayne [3] showed that CPG deformation and failure is initiated by weak annual rings. When they are located outside the gauge length, the recorded deformation is unreliable as observed by Levé et al. [8].

To support the suggestion of taking the full test specimen depth as gauge length instead of 60% of the depth, investigations by Hansen [9] are presented. The wood species used was Spruce with an average moisture content of 12%. Hansen [9] uses both gauge lengths simultaneously, from which the modulus of elasticity $E_{90}$ is derived, taking the linear part of the recorded load-deformation curve. At first, the standard EN408:2010 test piece of 90mm depth is taken and deformations recorded. Similar tests are performed with test pieces of 145mm and 220mm depth with 10 replicates each. The first column of Table 1 shows the specimen depth, while subsequent columns show the mean $E_{90}$ and the coefficient of variation for each gauge length. The coefficient of variation of $E_{90}$ for the 90 mm standard specimens (EN408) is only one third of the coefficient of variation, taking the 60% gauge length. Increasing the test specimen depth from 90 to 145mm and 220mm does not affect the $E_{90}$ value when taking the full depth. This is in contrast to when the 60% gauge length is taken, as the 60% gauge length delivers consistently higher values for the mean and variation coefficient.
Table 1. Overview of $E_{90}$ test results by Hansen [9], for load case A specimens, Spruce.

<table>
<thead>
<tr>
<th>Depth [mm]</th>
<th>$E_{90}$ gauge length [N/mm$^2$]</th>
<th>Var. coeff. [%]</th>
<th>$E_{90}$ gauge length 60% of total depth [N/mm$^2$]</th>
<th>Var. coeff. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>h=95</td>
<td>199.3</td>
<td>9</td>
<td>199.3</td>
<td>31</td>
</tr>
<tr>
<td>h=145</td>
<td>211.2</td>
<td>43</td>
<td>240</td>
<td>96</td>
</tr>
<tr>
<td>h=220</td>
<td>203.2</td>
<td>29</td>
<td>305.9</td>
<td>48</td>
</tr>
<tr>
<td>Mean</td>
<td>204</td>
<td></td>
<td>248</td>
<td></td>
</tr>
</tbody>
</table>

For this reason, all deformations used to evaluate the deformation models in this study are determined by using the full specimen depth as gauge length. This is done not only for the standard test specimen, but also for tests with all load cases as shown in Figure 1. During current revision stage of EN 408 a proposal is being discussed taking the total deformation instead of the 60%.

In Table 2, an overview is presented of the modulus of elasticity $E_{90}$ of the standard test specimens, tested in accordance with EN408 for all the wood species involved in this study (taking the full specimen depth as gauge length). In building practice, the structural design engineer will usually take the strength and stiffness values from a particular strength class system. For the wood species involved these values have been added in the last column. For Spruce the material was CE marked C24 (strength class), while for Poplar a value was taken from strength class C27 based on a mean density of 433kg/m$^3$. In strength classes, the material properties are given independent of the annual ring orientation and it is for this reason the annual ring orientation is not addressed in the test method of EN408 but taken at random. For the European situation, the strength classes are specified in CEN EN 338 [10].

Table 2. Overview of $E_{90}$ values, load case A, EN408

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Sample number</th>
<th>Number of tests</th>
<th>Mean $E_{90}$ [N/mm$^2$]</th>
<th>CV [%]</th>
<th>Strength class Value EN338</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>1</td>
<td>25</td>
<td>150</td>
<td>39</td>
<td>370</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>13</td>
<td>141</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>14</td>
<td>180</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10</td>
<td>170</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>158</td>
<td>48</td>
<td>370</td>
</tr>
<tr>
<td>Poplar</td>
<td>1</td>
<td>31</td>
<td>183</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>116</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>10</td>
<td>236</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td>159</td>
<td>32</td>
<td>380</td>
</tr>
<tr>
<td>Beech</td>
<td>1</td>
<td>10</td>
<td>976</td>
<td>25</td>
<td>700</td>
</tr>
<tr>
<td>Cumaru</td>
<td>1</td>
<td>12</td>
<td>911</td>
<td>8</td>
<td>1240</td>
</tr>
<tr>
<td>Akki</td>
<td>1</td>
<td>9</td>
<td>1082</td>
<td>33</td>
<td>1810</td>
</tr>
</tbody>
</table>
Due to a lack of knowledge when the strength class values were initially set, $E_{90}$ was taken as $E_0/30$ for softwood and $E_{90}=E_0/15$ for hardwood. Table 2 shows a considerable deviation for Spruce between the observed test value of 158N/mm$^2$ and the strength class value of 370N/mm$^2$. For Poplar the differences are 159N/mm$^2$ and 380N/mm$^2$ respectively.

In both cases the recorded modulus of elasticity $E_{90}$ is approximately 50% of the $E_{90}$ strength class value. In Hübner’s elaborate study [11], p. 49 reports a mean value for Beech of 1040N/mm$^2$ which is close to value of 976N/mm$^2$ in Table. However, based on the mean density of 629kg/m$^3$ the associated strength class value is D27 where $E_{90}$ is 700N/mm$^2$. For the other tropical hardwood species, Cumaru and Akki, a similar approach was taken with strength classes D65 and D80 respectively. Apparently, there are reasons to question the moduli of elasticity perpendicular to grain by the strength class system of EN 338.

3. Bearing strength of CPG models

The difference between the block test and the rail test is that the load is carried not only by the fibres directly under the loaded length $l$, but also by the neighbouring fibres, Fig. 2. Madsen [12] formulated an empirical model for the CPG strength. This model was later modified by Blass and Görlacher [13] by taking 30mm for contributing fibres adjacent to the loaded area, resulting in an effective length, $l_{ef}$ Eq. (1).

$$\frac{F_c}{b l_{ef}} = k_c f_{c,90}$$

(1)

Figure 4: Contributing fibres adjacent to the loaded area according to the Madsen/Blass and Görlacher model.

For fully supported load cases they suggest that $k_c=1,25$ and for solid wood and glued laminated wood 1,5. For other discontinuous support cases and other wood species other than softwood $k_c=1,0$. This model was adopted by the Eurocode 5 in EN1995-1-1:2008/A1.

A physical model, based on the equilibrium method assuming linear elastic-plastic material behavior, is formulated by Van der Put [14] following previous publications on the topic. A starting point for the (yield) theory is that the stress field assumed satisfies all boundary conditions with none of the stresses exceeding the
plastic failure criterion. The result is that for small strains an approximate effective length, $l_{ef}$, may be found assuming a 1:1 gradient of the stress spreading and a 1:1.5 gradient for larger strains (10%) where the strain hardening is fully developed, Eq. (2), Fig. 4.

$$\frac{F_c}{b \cdot l} = k_{c,90} f_{c,90,d}$$

with

$$k_{c,90} = \sqrt{\frac{l_{ef}}{l}} = \sqrt{\frac{l + 2h}{l}}$$

The dispersion of stresses is experimentally confirmed by optical and FEM tests carried out by Schoenmakers [15] and Petersen [16], both showed that outside $l_{ef} = l + 2h$, the stresses can be neglected. This confirmed the finding by Madsen et al [5].

### 3.1 Test data for the CPG strength models

In order to determine the ability of the models presented in predicting the CPG strength, appropriate test data was evaluated. The data base, with test results earlier used by Leijten et al [17], is extended with new test results on sawn timber. The wood species involved in the evaluation are Norway Spruce as the dominant wood species, and the hardwood species, Poplar, Beech, Cedar, Ash, Cumaru and Akki (Azobé), with average wood densities of 418 kg/m$^3$, 433 kg/m$^3$, 527 kg/m$^3$, 760 kg/m$^3$, 623 kg/m$^3$, 947 kg/m$^3$, and 1163 kg/m$^3$ respectively. The density for Ash was taken from Hübner [11]. All test specimens were conditioned at 60% RH and 20°C. Specimens of Spruce, Poplar, Beech, Cedar, Akki and Cumaru are cut from planks that vary in size suitable to test all the load configurations of. All tests are carried out according to the loading procedure of CEN EN408:2010 where the onset of yielding is determined by the dimension (depth) of the stressed area. A number of research reports not only reported the compressive strength at the onset of yielding, but also at 10% deformation.
Table 3: Overview of wood species and test program for CPG strength

<table>
<thead>
<tr>
<th>Wood Species</th>
<th>num tests</th>
<th>samples</th>
<th>num tests</th>
<th>Samples</th>
<th>density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>1118</td>
<td>119</td>
<td>554</td>
<td>62</td>
<td>947</td>
</tr>
<tr>
<td>Cumaru</td>
<td>48</td>
<td>11</td>
<td>37</td>
<td>6</td>
<td>1163</td>
</tr>
<tr>
<td>Azobé</td>
<td>114</td>
<td>26</td>
<td>114</td>
<td>26</td>
<td>448</td>
</tr>
<tr>
<td>Poplar</td>
<td>137</td>
<td>22</td>
<td>135</td>
<td>21</td>
<td>433</td>
</tr>
<tr>
<td>Beech</td>
<td>73</td>
<td>12</td>
<td>25</td>
<td>10</td>
<td>433</td>
</tr>
<tr>
<td>Ash</td>
<td>52</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>760</td>
</tr>
<tr>
<td>Ceder</td>
<td>25</td>
<td>10</td>
<td>25</td>
<td>10</td>
<td>527</td>
</tr>
<tr>
<td>coniferous</td>
<td>1118</td>
<td>119</td>
<td>554</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>hardwood</td>
<td>449</td>
<td>83</td>
<td>336</td>
<td>73</td>
<td></td>
</tr>
</tbody>
</table>

The reported test results covered all the load configurations as shown in Fig. 1. Table 3 summarises the number of test results and samples per wood species that were used in the strength evaluation. The bottom two lines summarise the data divided in coniferous and deciduous wood species.

### 3.2 Results of the CPG strength evaluation

The evaluation results of Spruce and all hardwood species together, are split into two main parts representing the test data for the onset of yielding and the other one for 10% deformation, shown in Figures 6 to 11. In the figures, only the sample mean values were considered. Furthermore the graphs show two curves. One of the curves runs diagonally and the other is the regression curve that take the formulation $y=ax$ and, as such, is forced to start at the origin of the graphs. The equations and the $R^2$ values are provided in each graph.

![Figure 6: Test results versus the Madsen/Blass & Görlacher model (onset of yielding) Spruce.](image-url)
Figure 7: Test results versus the Van der Put model prediction (onset of yielding) Spruce.

Figure 8: Test results versus the Madsen/Blass & Görlacher model (10% deformation) Spruce.

Figure 9: Test results versus the Van der Put model prediction (10% deformation) Spruce
Figure 10: Test results versus the Van der Put model prediction (onset of yielding) hardwood.

Figure 11: Test results versus the Van der Put model prediction (10% deformation) hardwood.

An overview of the linear regression results are presented in Table 4. As the model of Madsen/Blass & Görlacher as given in the Eurocode EN1995-1-1:A1 apply only to softwood, there is no evaluation when dealing with the hardwood results.

Table 4: Overview of regression results $y=lx$

<table>
<thead>
<tr>
<th>Wood Species</th>
<th>Model</th>
<th>$a$</th>
<th>$R^2$</th>
<th>$a$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>onset of yielding</td>
<td></td>
<td></td>
<td>10% deformation</td>
<td></td>
</tr>
<tr>
<td>Spruce</td>
<td>Van der Put</td>
<td>0.973</td>
<td>0.47</td>
<td>0.764</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Madsen/Blass &amp; Görlacher</td>
<td>1.281</td>
<td>0.28</td>
<td>0.919</td>
<td>-0.05</td>
</tr>
<tr>
<td>Hardwood</td>
<td>Van der Put</td>
<td>1.045</td>
<td>0.76</td>
<td>0.73</td>
<td>0.540</td>
</tr>
<tr>
<td></td>
<td>Madsen/Blass &amp; Görlacher</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The results in Table 4 show that the Van der Put model constantly has the highest value for the coefficient of determination, $R^2$ independent of the wood species,
and the $a$-values (in $y=ax$) are near to 1.0. For the 10% deformation the predictions using the Van der Put model are consistently on the safe side, $a = 0.75$.

- Considering the regression results at the onset of yielding and at 10% deformation, it can be concluded that the model by Van der Put is more reliable than the Madsen/Blass & Görlacher model.

- For the 10% deformation results the Van der Put model underestimates CPG strength of Spruce and the hardwood species by 25%.

In Leijten [11] it is shown for a smaller data base that the compressive strength is not correlated with the dimensions of the specimen or the height to width ratio.

### 4. Bearing deformation of CPG models

Deformation models for bearing are hard to find in literature. In 1982, Madsen et al. [5] published a bearing deformation model. The model is based on Hook's Law (strain is proportional with the applied stress) as a starting point. The spreading of the bearing stresses is recognised and the total deformation $\delta$ is dependent on the number of parameters. The difficulty is that the parameters $l_1$ and $l_2$ have, as stated by the author, no physical meaning but are empirical in nature and thus do not relate to the CPG. In the European Design Code of 1987 [18], another empirical model is presented but only for the load cases B and F. Hook's Law is again applied but now modified with a factor $k_u$. It is assumed this factor is determined by evaluation of test results. It was F. Mårtensson [19] who proposed an empirical deformation model that once more takes Hook's law as a starting point. Apparently this model is too limited in its application to be accepted by the timber design codes, as none of the structural timber codes have adopted it. The models mentioned above will be left out of the evaluation, either because they do not distinguish between load cases or they contain unknown parameters. Van der Put [14] as well as Blass and Görlacher [13] came up with a deformation model similarly based on Hook's law, but with the assumption of a certain spreading of the bearing stresses in grain direction, combined with the assumption of a linear elastic material behaviour. The disadvantage of their model is that the model equation is load case dependent. A different approach using the same starting point of stress spreading is based on the following. Calculate the average stress perpendicular to grain taken at the loaded area and the support area and apply Hook's law:

$$
\sigma_{avg} = \frac{F_{c,90}}{2b} \left( \frac{1}{l} + \frac{1}{l_{ef}} \right)
$$

$$
\delta = \varepsilon h = \frac{\sigma_{avg} h}{kE_{90}} = \frac{F_{c,90} h}{2bkE_{90}} \left( \frac{1}{l} + \frac{1}{l_{ef}} \right)
$$

(3)

In Eq.(3) the calibration parameter $k$ is a coefficient to change the modulus $E_{c,90}$ in an apparent value as mentioned earlier. The necessity for this parameter depends
on the evaluation of the performance of the deformation model. The depth $h$ can either be the full depth of the beam as in load cases B and F, or the so-called effective depth $h_{ef}$ in load cases G and H. In the load cases C, D and E, there is more than one stress field. The total deformation can be determined by adding the deformation of each stress field. This method of adding deformations of separate stress fields is also easy to apply to more complex load cases such as C and J, Figure 12 and 13. A general expression for the model of Eq.(3), accounting for a number of stress fields $n$, can be written as Eq.(4).

$$
\delta = \frac{F_{c,90}}{2bkE_{90}} \sum_{n=1}^{n} h_n \left( \frac{1}{l_n} + \frac{1}{l_{n+1}} \right)
$$

where:

- $\delta$ is the total bearing deformation,
- $F_{c,90}$ is the load perpendicular to grain,
- $b$ the width of the loaded area,
- $k$ modification factor to change $E_{90}$ into an apparent value
- $E_{90}$ is the modulus of elasticity of the wood species involved perpendicular to grain,
- $n$ are the number of stress fields,
- $h_n$ the distance between the loaded and the bearing area of each individual stress field,
- $l_n, l_{n+1}$ the loaded length of the loaded area, $n$ and bearing area, $n+1$.

The advantage of the last approach is that bearing deformation equation does not change by load case which is beneficial for application in a design code. This stress spreading approach can be applied to all load cases. As shown in Figure 12 for load case C, the total deformation can be calculated by splitting up the stressed area into two parts. One caused by the top loaded area with loaded length $l$ and depth $h_1$, and the second caused by the bottom support with loaded length $l_s$ and depth $h_2$, having an common intersection length indicated by the horizontal dotted line, the so-called effective length $l_{ef}$. The total deformation is approximated as the

![Figure 12: Stress spreading gradient for load case C](image)


summation of the deformation of both stressed areas. Similarly, this can be applied for close spaced loads and to situations where the loads are close to the end face, load case F and J, Figure 13. A dotted horizontal line parallel to grain divides the stressed areas at locations where they start to either interfere with other stressed area or touch the end face.

![Figure 13: Load cases F and J with interfering stress areas.](image)

The approximated contribution of each stressed area in the total deformation has to be determined following this procedure. In principle, load cases G and H are the same as B because at a certain depth the deformation perpendicular to grain vanishes, Leijten et al.[20], Figure 14. For these discrete load cases the depth of the beam $h$ is replaced by the effective depth $h_{ef}$ which is equal to 40% of the total beam depth or 140mm, whichever is the smallest. This research result applies to Spruce. For other wood species an FEM analyses can be applied to check the validity of this value.

![Figure 14: The effective depth for not fully supported load cases](image)

### 4.1 Test Data for the CPG deformation model

The test data for the bearing deformation model originates from student research reports at the TU-Eindhoven, and there is also a limited number of test data from literature. What is important for the evaluation is that the all tests are performed according to the procedure given in EN408:2010. An overview of the variation in dimensions of the tested pieces, mainly sawn timber, is presented in Leijten [21]. Only in the case of Norway Spruce is a distinction made between structural timbers (ST) and glued laminated timbers (GLT). The table also includes standard test specimen dimensions in accordance with standards like ASTM- D143, AZ/NZ
and ISO 13910. For load case J, the spacing between the load areas and the distance to the end face have been varied from 30mm to three times the specimen depth 3h. The total number of tests performed, including tests reported by Hansen [9], Moseng and Hagle [22] and Augustin and Schickhofer [23], are presented in Table. The number of tests for Cumaru is limited, covering only load case B and D with 12 results each. The deformation test results, however, are in line with the range that is found for the other wood species and load cases.

Table 5. Number tests per wood species and samples

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Number of tests</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>794</td>
<td>72</td>
</tr>
<tr>
<td>Poplar</td>
<td>191</td>
<td>28</td>
</tr>
<tr>
<td>Beech</td>
<td>41</td>
<td>6</td>
</tr>
<tr>
<td>Akki/Azobé</td>
<td>114</td>
<td>26</td>
</tr>
<tr>
<td>Cumaru</td>
<td>24</td>
<td>2</td>
</tr>
<tr>
<td>Total number</td>
<td>1164</td>
<td></td>
</tr>
<tr>
<td>Total number of samples</td>
<td>134</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Results of the CPG deformation evaluation

In the following, the ability of the model to predict the experimentally determined bearing deformation is investigated. The model requires an input value for the modulus of elasticity $E_{90}$, which is taken from Table. The performance of the model Eq.(4) is shown in Figure only for the wood species Spruce.

![Figure 15: Deformation prediction, Eq(4) versus onset of yielding test data of Spruce](image)

The number of samples is 72, representing 794 test results covering all load cases. When the intersection with the origin is left free, the regression curve has the coefficient of determination, $R^2=0.674$ while the deformation by the model is underestimated by 15% approximately ($y=0.88x$). When the regression curve intersects at the origin, no significant changes occur in the parameters just mentioned. How the model of Eq.(4) performs, considering the results of the hardwood test speci-
mens, is presented in Figure 16 with 62 samples, representing 370 test results. The result in terms of the coefficient of determination, $R^2 = 0.227$ is much less than in Figure 15 for Spruce. The deformation is underestimated about 25%. The merging of the test data of Figure 14 and 15, results in Figure 17. This represents all wood species and all load cases with a total of 134 samples, comprising 1164 test results altogether. The coefficient of determination $R^2$ of the trend line is 0.617. The deformation model of Eq.(4) underestimates the deformation by approximately 15% in terms of mean deformation.

![Figure 16: Deformation prediction Eq.(4) versus onset of yielding hardwood test data.](image1)

![Figure 17: Deformation prediction Eq.(4) versus onset of yielding Spruce + hardwood test data.](image2)

What has been discussed earlier is the option of applying a modification factor $k$ that was introduced to modify the modulus of elasticity, $E_{90}$ to an apparent value to cater for the non-linearity of the load deformation curve at the onset of yielding. It was also concluded that the model using the $kE_{90}$ with $k=1.0$ constantly underestimated the deformation at onset of yielding. Varying the value of $k$ does not change the $R^2$ but the mean model predictions improve considerably as shown in Table 5. For design purposes a good value is $k=0.85$ but the choice is arbitrary. This value can be substituted in Eq(3) and Eq(4).
Table 6: Varying the modification factor $k$

<table>
<thead>
<tr>
<th>Material</th>
<th>$k=1.0$</th>
<th>$k=0.9$</th>
<th>$k=0.85$</th>
<th>$k=0.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>0.8798</td>
<td>0.9775</td>
<td>1.035</td>
<td>1.0997</td>
</tr>
<tr>
<td>Hardwood</td>
<td>0.7619</td>
<td>0.8437</td>
<td>0.8919</td>
<td>0.9461</td>
</tr>
<tr>
<td>All data</td>
<td>0.851</td>
<td>0.9449</td>
<td>1.0001</td>
<td>1.0623</td>
</tr>
</tbody>
</table>

5. Eurocode 5 design proposal

Summarizing, it is concluded that the model of Van der Put with a stress spreading gradient of 1:1 is an excellent tool to determine the CPG strength at onset of yielding. At 10% deformation, however, the model underestimates the strength by 25% using a stress spreading gradient of 1:1.5. In accordance with the Eurocode safety format at the ultimate limit state (ULS), a design value for the CPG strength is found by applying the factor $k_{\text{mod}}$ and the partial factor $\gamma_m$ as follows:

For stress spreading gradient 1:1

$$\frac{F_{c,90,d}}{bl} = \sigma_{c,90,d} \leq \frac{l_{ef}}{l} \frac{k_{\text{mod}}}{\gamma_m} f_{c,90,k}$$

deflection:

$$\delta = \frac{F_{c,90}}{1.7E_{90}} \sum h_n \left( \frac{1}{l_n} + \frac{1}{l_{n+1}} \right)$$

For stress spreading gradient 1:1.5

$$\frac{F_{c,90,d}}{bl} = \sigma_{c,90,d} \leq 1.25 \frac{l_{ef}}{l} \frac{k_{\text{mod}}}{\gamma_m} f_{c,90,k}$$

deflection $\delta = 0.1 \ h$ or $0.1h_{\text{ef}}$

Structural timber designers now have, in principle, a choice to use either of the CPG strength equations with associated deformation at ULS. It requires, however, more effort to calculate the results of both equations as the stress gradient is different. Ways to convert the strength of one equation into the other are typical code design problems. For this reason, the Eurocode Working Group that considered a proposal based on this research opted for the approach with a stress spreading gradient of 1:1 which resulted in an onset of yielding deformation as ULS, Figure 18. The advantage is that, for the strength and deformation, accurate design formulas are available. The next step in the design proposal is the conversion of the characteristic CPG strength to a design value applying $k_{\text{mod}}/\gamma_m = 0.8/1.3 \approx 0.615$ (taken from EN1995-1-1:2004) to the characteristic strength, $f_{c,90,k}$ covering most cases. Figure 18 shows that by doing so the stress level for the ULS design goes down where timber behaves in a linear elastic manner. The CPG capacities calculated in this way are far less than the capacity according to current rules in EN1995-1-1:A1. In this way no use is made of the guaranteed plastic behaviour at the ULS.
A method to repair this situation is the introduction of a new parameter, \( k_p \), that accounts for the amount of compression deformation. The value is the inverse of applying \( k_{mod}/\gamma_m \), so \( k_p = \gamma_m/k_{mod} = 1/0.615 = 1.63 \). At this point, the strength level is back at the onset of yielding. Evaluation of the data base shows that the mean strain at this stress level is 2.40% with a standard deviation of 0.6%. If desired this deformation can more accurately be calculated using the deformation model with a stress gradient of 1:1. Considering the load-deformation curves of many tests the stiffness at serviceability load level is approximately twice as high compared to the apparent stiffness for the onset of yielding. In the calculation of the bearing deformation the stiffness might therefore be doubled. To take account of the benefit that strength increases with increasing deformation, the following procedure is followed for higher strains than at the onset of yielding. Analysing the data base of test results, the mean CPG strength at 10% deformation appears to be 1.46 times the mean strength at onset of yielding. For Spruce and the hardwood data the results are very close 1.460 and 1.465 with a standard deviation of 0.27 and 0.23, respectively. This means an approximate value of \( k_p = 1.63 \times 1.46 = 2.3 \). For even larger deformation up to 20% only test data is available by Moseng M & Hagle D [22]. Their data shows a strength increase of approximately 1.30 resulting in \( k_p = 2.3 \times 1.3 = 3.1 \). All these consideration leads to Table 7 where an overview is given of the appropriate \( k_p \) values.

**Table 7: Values for \( k_p \)**

<table>
<thead>
<tr>
<th>Ultimate design situation</th>
<th>( k_p )</th>
<th>Expected mean deformation in % of the (effective) member depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation may affect member of system stability</td>
<td>0.67</td>
<td>1%</td>
</tr>
<tr>
<td>Deformation may not affect member of system stability</td>
<td>1.6</td>
<td>2.5%</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>10%</td>
</tr>
<tr>
<td>Deformation may not affect member of system stability and provided member depth, ( h \times 100 \text{mm} ) and the width ( b \geq h )</td>
<td>3.1</td>
<td>20%</td>
</tr>
</tbody>
</table>
6. Conclusion
A bearing strength and stiffness model is evaluated. The most promising strength model is the one by Van der Put [14] that uses stress spreading. It is explored of its ability to predict the strength at the onset of yielding deformation as well as the strength at 10% deformation. As the strength model allows two stress spreading gradients associated with both deformations, they are tested using test results of an elaborate data base. This data base consists of tests performed with the wood species Norway Spruce as the only softwood and the hardwoods, Beech, Ash, Cedar, Poplar, Cumaru and Akki. The strength data of Norway Spruce comprised 119 and 74 samples of 1118 and 655 tests for the onset of yielding and at 10% deformation respectively. For the hardwoods, the values are 83 and 73 samples and 449 and 336 tests respectively. The strength prediction at the onset of yielding, taking a stress spreading gradient of 1:1, is more accurate and reliable than the current model in Eurocode 5 EN1995-1-1: A1. At 10% deformation, however, by taking a stress spreading gradient of 1:1.5 the mean strength prediction underestimates the mean test result by 25%. In general, the mean difference between the strength at the onset of yielding and at 10% deformation is 1.46 for both Norway Spruce and all hardwood species. Analysing the few results available for deformations of 20% indicates another strength increase of approximately 1.3, Table 7. The bearing deformation model applied to Norway Spruce only underestimates the deformation by 15%, but this can be accounted for by introducing a factor to increase the stiffness. The deformation model for hardwood underestimates the mean deformation by 25% but the scatter of the results is high, $R^2=0.23$.
In addition to the evaluation of the test data and the model performance, the background is given how the parameters for the new generation Eurocode 5 are developed.

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9. Information on the author

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